CONCEPT FOR MULTIPLE OPERATIONS AT NON-TOWER NON-RADAR AIRPORTS DURING INSTRUMENT METEOROLOGICAL CONDITIONS

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Abstract

A concept for multiple operations during Instrument Meteorological Conditions (IMC) at non-tower, non-radar airports is described. The objective is to provide an automated service which will support separation assurance for aircraft operating in the airport airspace. This type of service will enable the use of a large number of airfields which currently have limited use in IMC. The service must be provided with minimal infrastructure and at low cost.

The concept is based on a centralized automated airport management module and distributed, on-board navigation tools. The airport management module serves as an arbiter and sequencer. It receives requests from aircraft via a data link and grants or denies access. The airport management module also provides estimated times of arrival when access is granted and an “expect further clearance” time when access is denied. On-board avionics tools provide situational awareness and generate advisories to be able to meet estimated times of arrival.

The concept is being developed such that operations into and out of the non-tower, non-radar airport are compatible with the existing National Airspace System (NAS). A system simulation has been developed based on this concept. This paper describes the system functionality, system requirements, and operations. Preliminary results of the system simulation with various aircraft mixes, wind speed and directions, and arrival rates are presented.

The work presented in this paper does not describe the SATS HVO concept of operations [1]. It is a feasibility study and used to develop methods for verification.

1. Introduction

Air transportation in the United States and the rest of the world is mostly performed by commercial carriers. Since deregulation, commercial transportation has evolved into a hub-and-spoke system. The hub-and-spoke system has clear operational and economical advantages for the airlines over a point-to-point system. However, the hub-and-spoke system also has some significant drawbacks, which have become more accentuated as air travel has increased in the last decade. Saturation of hub airports with resulting delays, the need for connections when traveling between medium or small cities, and the increase in overall door-to-door travel time are some of the major concerns.

Although there are more than 5400 public use airports in the United States [2] the majority of these airports are underutilized. Underutilization is due to lack of commercial service, lack of facilities, and a public perception that small airplanes are not a viable mode of transportation. General aviation aircraft are mostly used for recreation or for special purposes.

Airports without facilities such as Instrument Landing Systems, control towers, radar coverage, etc. are limited in the number and types of operations they can support. A person using such airports may not have a high level of confidence that they will be able to arrive at their destination and that they will arrive on time to meet their commitment. The loss of productivity and inconvenience may preclude business and other travelers from using these airports.

Providing air traffic services at airport which currently lack such services will significantly expand the options for travelers in the medium to small markets. Emerging and existing technologies such as Automatic Dependent Surveillance-Broadcast (ADS-B) [3], Global Positioning System (GPS) [4], Wide Area Augmentation System (WAAS) [5] and others could provide the necessary technology and infrastructure to develop air traffic services at reduced cost, as compared to radar installations and other current methods of traffic surveillance and navigation aids.

Operations to non-tower non-radar airports

Airports without radar coverage rely on procedural separation during Instrument Meteorological Conditions (IMC). IMC exists when conditions are below weather minima specified for the class of airspace. Under this condition, only instrument rated pilots can fly under instrument flight rules. Procedural separation is used where surveillance data is not available or in uncontrolled airspace. In non-radar airports, Air Traffic Control (ATC) provides separation services to Instrument Flight Rule (IFR) aircraft by a method of "one-in/one-out." That is, only one IFR aircraft is given access to the airspace at a given time. Once access is granted to an aircraft to enter the airspace, no other IFR operation is permitted until the aircraft granted access departs the airspace or closes its flight plan. As expected, this method results in an underutilization of the airport facility.

In [6], Conway and Consiglio describe a system to automate the one-in/one-out method of procedural separation. This system proposes a special designation airspace around the airport, a ground based system which automates the method for procedural separation, a data communication link between the ground based automation and aircraft intending to use the airport facility, protocols governing access to the airspace, and procedures for transition between the in-route airspace and the airport airspace.

Tobias and Scoggins [7] describe an automation system, based on artificial intelligence, which attempts to replicate traditional ATC IFR services. The system generates routes and vectoring to provide sequencing and separation into and out of the airport airspace. VHF radio communication is used to transmit synthesized voice commands to aircraft.

In this paper, we describe a concept for multiple operations to non-tower, non-radar airports during IMC. This concept does not automate typical ATC services like in Tobias and Scoggins' work and does not provide ground base aircraft vectoring. Rather, it is an automated arbiter and sequencer that, together with state broadcasting and enhanced traffic displays, allows the pilot to accept responsibility for separation.

The concept is based on a special designation airspace called the Self Controlled Area (SCA), a ground based automation system called the Airport Management Module (AMM), data communication between the AMM and the aircraft operating to and from the airport facility, aircraft data broadcast of state information, and on-board navigation tools and navigation displays with traffic information.

Section 2 describes the operations concept and discusses possible ways to incorporate the specially designated airport facility into the present National Air Space (NSA). Section 3 describes the simulation. Section 4 gives simulation results of the concept implementation. Section 5 is a summary and future work.

2. Concept of Operations

The system operates with four main components: 1. A Self Controlled Area surrounding the airport facility where pilots accept responsibility for separation; 2. An Airport Management Module which receives request from aircraft to access the SCA and grants or denies access; 3. A data communication link between aircraft and the AMM; 4. State data broadcast from aircraft capable of operating in the SCA and associated on-board navigation and traffic displays.

The Self Controlled Area

The Self Controlled Area (SCA) is a three dimensional airspace surrounding the airport facility. Depending on geography and location, the shape of this volume could vary. For illustration purposes and for the experimental results presented in this paper, we have selected a cylinder of 12 nautical mile radius and 4000 feet height above ground level, as shown in Figure 1.

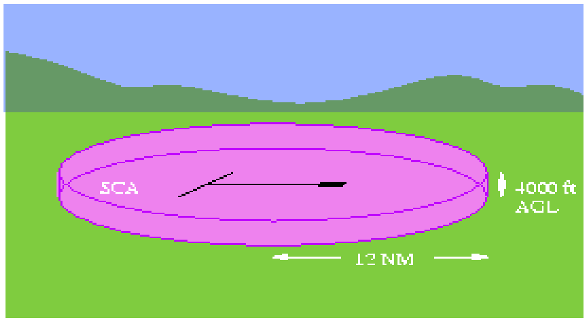

Figure 1. Self Controlled Area

The design of the SCA includes a generic GPS standard instrument approach procedure and a "T" structure as shown in figure 2.

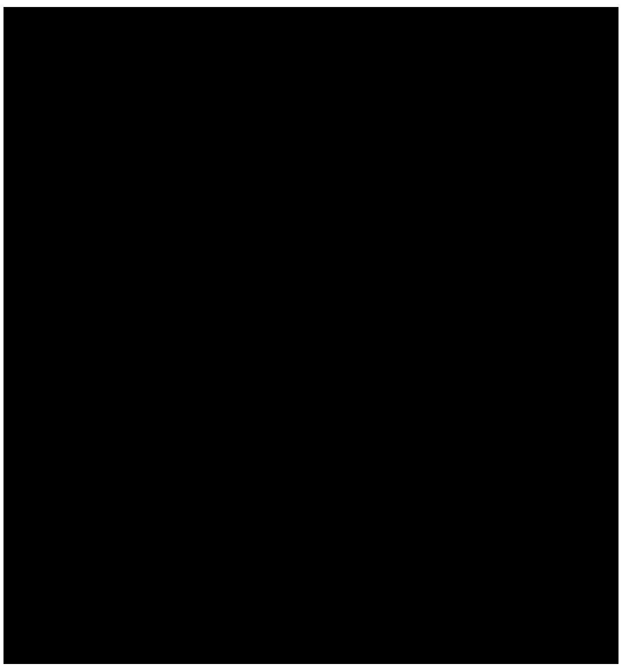

Figure 2. Basic "T" Design

For the "T" configuration, aircraft approaching the terminal area from the base right shall proceed directly to the IAF_R when granted access; approaches from base left shall proceed directly to the IAF_L; approaches from the straight in area shall proceed directly to the IF.

It is important to note that aircraft entering the SCA accept responsibility for separation. The system automation does not provide vectoring and commands for separation.

Airport Management Module (AMM)

The AMM is a centralized automated system which will typically reside in the airport grounds. The AMM is an arbiter to the Self Controlled Area. It receives requests from aircraft wanting to enter the SCA and grants or denies access. It will only grant access to the SCA when the requesting aircraft will be time separated with all other aircraft already given access.

The AMM grants or denies entry into the SCA based on nominal approach paths, aircraft performance calculations, and possible conflicts with other aircraft already given access to the SCA. The AMM maintains a database of aircraft types and performance characteristics for the aircraft types.

To determine grant or denial of access, the SCA is divided into 6 regions, shown in Figure 3. The SCA is divided into regions to obtain simplified access criteria, without overly constraining the airspace.

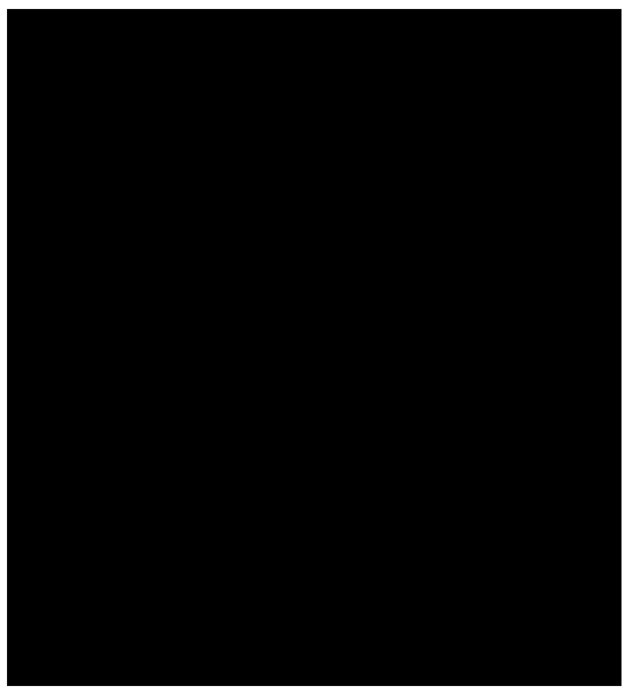

Figure 3. SCA Access Regions

The entry criteria are based on the operating region of the aircraft. For example, an aircraft entering region 1 will have to be time separated at the SCA boundary, IAF_R, IF, FAF, and RT, with any other aircraft entering region 1. However, an aircraft entering region 1 will only have to be time separated at the IF, FAF, and RT with an aircraft entering region 5.

When the AMM grants access to the SCA, it generates Estimated Time of Arrivals (ETAs) to the SCA boundary, all fixes, and the runway threshold, which the pilot might use as guidelines for navigation. When a request to enter the SCA is denied, the AMM produces an Expect Further Clearance (EFC) time, which is an approximate time when the aircraft will be given access.

Data Communication Link

The data communication link is a two-way link, which allows aircraft to send requests to the AMM and receive from the AMM request decisions, ETAs and EFC information.

State Data Broadcast

Aircraft operating or intending to operate in the SCA, broadcast their state information. Aircraft also receive broadcasts from other aircraft and this information is used for situational awareness, navigation and conflict detection. Data broadcast could be based on ADS-B or other aircraft data broadcast standard.

Operations within the Air Traffic Control (ATC) system

The automated airport access system could be integrated within the ATC system by means of a procedural transition between the ATC controlled airspace and the automated airport. In addition to the SCA, the system requires designated holding fixes outside of the SCA. Figure 4 illustrates a possible geometry for such a system.

Figure 4. SCA Integrated for Operations with ATC

The following example is the typical steps a pilot will follow when operating from a non-automated airport (KNWX) to an automated airport (KAYZ).

1. Pilot files a flight plan to fly from KNWX to KAYZ using holding fix BAMBY.

2. ATC controls aircraft departure.

3. ATC vectors aircraft to KAYZ and clears aircraft to BAMBY when fix is not occupied.

4. As aircraft approaches BAMBY (within r nautical miles), it requests to the AMM entry into the SCA.

5a. If access is immediately granted to the SCA, the pilot notifies ATC that he is leaving the BAMBY holding fix and proceeding to the SCA. ATC terminates services and the pilot accepts responsibility for separation. BAMBY holding fix becomes unoccupied and ATC can clear other aircraft to this fix.

5b. If access is denied to the SCA, the aircraft enters the holding pattern at BAMBY holding fix. The fix will remain occupied until the aircraft notifies ATC that it is proceeding to the SCA. It is also possible for ATC to clear more than one aircraft to a holding fix at different altitudes. For example, clear to BAMBY at 3000 and clear to BAMBY at 4000.

Operations in a free-flight environment.

In a free-flight environment, flight crews are responsible for flight separation in the National Air Space [8]. Transition between the free-flight airspace and the SCA is as follows:

1. Aircraft approaches automated airport.

2. Aircraft requests to the AMM entry into the SCA.

3a. If access is granted to the SCA, the aircraft proceeds directly to designated initial fix.

3b. If access is denied, aircraft must remain outside the SCA and maintain separation from other aircraft in the vicinity.

3. Simulation

A simulation has been developed to evaluate the feasibility, efficiency, and performance of the concept. It simulates operations where the SCA is within a free-flight environment. It is a batch simulation (no pilots are involved) and implements the AMM decision logic, an onboard navigation advisor which gives heading, altitude, and speed advisories, together with models of aircraft dynamics (including winds), and models of pilots. Figure 5 depicts the main blocks of the simulation.

Figure 5. Simulation Block Diagram

The simulation is written in Java® and each aircraft is an instantiation of an object for a given aircraft type. In this experiment, only two types of aircraft have been implemented: a Cessna 172 and a LearJet 45. These aircraft are meant to be representative of slow piston aircraft and fast jet or turbo prop aircraft. Hence forth in this paper, piston aircraft refers to slow aircraft and jet to fast aircraft. The speed profiles used for these aircraft are shown in Figure 6. The speed profiles show 3 speeds: The initial speed, nominal arrival speed (nomA), and nominal final speed (nomF). The initial speed is the calibrated air speed (CAS) of the aircraft when it requests entry into the SCA. It is assumed that the initial speed is always equal to or greater than nomA.

The speed profiles are used by the AMM and the onboard navigation advisor. The AMM uses the speed profile, together with path and winds, to calculate ETAs to boundaries and fixes. The onboard navigation advisor uses the speed profile to generate speed guidance to meet ETAs.

Figure 6. Speed Profiles

AMM operation

The AMM receives requests to enter the SCA and grants or denies access. The system is based on a first-come-first-serve method of arrival. To implement access control, the AMM maintains two aircraft lists: An access request list, and an access granted list. When the AMM receives a new request, it puts the request in the request list. Based on the type of the aircraft, the nominal estimated time of arrivals (ETAs) are calculated. These ETAs are to the SCA boundary, initial arrival fix (IAF), intermediate fix (IF), final arrival fix (FAF), and runway threshold (RT). The AMM then compares the ETAs of the requesting aircraft with the ETAs of all aircraft in the access granted list. The requesting aircraft ETAs must maintain a T_s time separation with the ETAs of all other aircraft in the access list and the time separation must be such that overtaking cannot occur in the SCA. Access will be granted when, for each aircraft already granted access to the SCA, the requesting aircraft will be ahead by T_s on all relevant points (fixes), or behind by T_s on all relevant points. T_s is the required time separation. In mathematical terms, access is granted when the following predicate holds true:

$$\forall j : ((\forall fix : ETA^{req}_{fix} - ETA^{j}_{fix} \geq T_s) \ OR$$
$$(\forall fix : ETA^{req}_{fix} - ETA^{j}_{fix} \leq -T_s))$$

where j is the index of aircraft in the access list, *req* is the requesting aircraft and *fix* are all the points where time separation is to be maintained.

When access is granted, the requesting aircraft is removed from the request list and put into the access granted list. The AMM broadcasts a request granted message, which includes initial arrival fix assignment and ETAs to SCA boundary and fixes. The aircraft is expected to proceed directly to the assigned initial arrival fix as described in GPS procedures for T approaches, Federal Aviation Regulations/Aeronautical Information Manual (FAR/AIM) [9].

When access is denied, the requesting aircraft is kept in the request list and an expect further clearance (EFC) time is calculated and broadcast to the requesting aircraft. The aircraft is expected to remain outside of the SCA.

The AMM calculates the ETAs in the following manner:

- It receives, from aircraft transmissions, the aircraft heading and location.
- It receives the aircraft ground speed or calculates ground speed from consecutive locations.
- From ground speed, heading, and prevailing winds, it calculates the aircraft true air speed (TAS).
- Using the calculated TAS, the AMM calculates the aircraft ground speed should the aircraft were to turn to the IAF. This speed is the initial speed.
- The nominal path is calculated.
- Using the speed profile for the type of aircraft and the nominal path, the AMM generates ETAs to the SCA boundary, all fixes, and runway threshold.

On-Board Navigation Advisor

The on-board navigation advisor module generates heading, altitude, and speed guidance to navigate the nominal arrival path. When the aircraft has been cleared to the SCA, the navigation module uses the published approach procedure, geographical data and assigned IAF to generate the guidance. The heading, altitude, and speed guidance will follow a nominal speed profile.

The navigation module will give guidance to enter into a holding pattern when access to the SCA has been denied.

Pilot Model

The pilot module is a low fidelity model of a pilot. It receives current state information from the aircraft dynamics module. It also receives heading, altitude, and speed guidance from the navigation module. With this information, the pilot model makes changes to the aircraft bank angle, horizontal speed and vertical speed to conform to the nominal path. The pilot model introduces a level of uncertainty to the simulation. The pilot model has a reaction delay time to the guidance and it does not perform changes when the difference between the current state and the guidance is bellow a set threshold. Pilot uncertainty produces aircraft paths that are off the nominal path within error bounds.

Generation of Aircraft and Arrival Rate

Arrival rates can be selected at the beginning of the simulation. To make the simulation more realistic, aircraft are not generated in the vicinity of the target airport. In the simulation, aircraft "take off" from airports 30 to 400 miles away from the target (destination) airport and fly towards the target airport. The distance and origination of the aircraft are random which produces a quasi-random arrival rate.

For example, at a 10 aircraft per hour arrival rate, 15 aircraft could arrive in a 15 minute interval and 5 aircraft in the next 1 hour and 45 minutes interval. The arrival rate selected is the *average* arrival rate over the simulation duration.

4. Results

The results presented in this section are for an automated airport within a free flight environment. Aircraft request entry into the SCA approaching the airport from any direction outside the SCA periphery. Time separation is set at 3 minutes and pilots request entry when at 25 nautical miles from the center of the SCA and at or below 8 thousand feet AGL (Above Ground Level). Runway orientation is north to south with aircraft landing to the south (runway 18).

Results show average and maximum delay as a function of various aircraft mixes, arrival rates and wind conditions. Delay is the difference between the time when an aircraft request entry into the SCA and the time when access is granted. Results presented in this section are for a 48 hour period of operation. The first three graphs, figures 7, 8 and 9, are average and maximum delay as a function of average arrival rate for 100/0, 50/50, and 0/100 percent piston/jet ratios, respectively. The vertical axis for these three graphs is on a logarithmic scale (hours:min:sec) which shows in all cases an exponential and possibly double exponential growth in delay as a function of arrival rate.

Figure 7. Delay vs. Landing Rate, 100% Piston, 20 Knot Wind out of the South

Figure 8. Delay vs. Landing Rate, 50% Piston 50% Jet, 20 Knot Wind out of the South

Figure 9. Delay vs. Arrival Rate, 100% Jet, 20 Knot Wind out of the South

For 100% piston and 100% jet, an average arrival rate of 15 per hour produces average delays of approximately 4 minutes. This figure is comparable to the average delay rate for commercial operations in Europe (4 minutes) [10] and below the average delay rate for commercial operations in the U.S. (9 minutes) [11].

Further increase in arrival rate towards the theoretical maximum of 20 per hour (for 3 minutes time separation) produces delays which are judged to be unreasonable. In the case of a 50 percent piston/jet mix, the jet class suffers a disproportioned number of delays and delays are judged to be too high even at rates of 12 arrivals per hour. A possible solution to the excessive delays for fast aircraft is to base the request distance on the type of aircraft. Faster aircraft can request entry into the SCA farther away than slower aircraft. In essence, a request based on time-to-go rather than on distance-to-go.

Figure 10 shows delays as a function of aircraft mix for an average arrival rate of 10 per hour. For jet aircraft, average and maximum delays increase for any piston/jet mix over an all jet scenario. For piston aircraft, average and maximum delays are reduced for a 10/90 piston/jet mix over an all piston scenario. In general, piston aircraft delays are not significantly affected by the inclusion of jet aircraft. Jet aircraft delays, however, are detrimentally affected to a high degree by the inclusion of slow aircraft operations. Again, taking into account the aircraft performance in the request procedure could alleviate this problem.

Figure 10. Delay vs. Aircraft Mix, 10 Landings/Hour Average, 20 Knot Wind out of the South

Figures 11 and 12 show the impact of winds on system performance. Winds from 0 up to 20 knots do not affect the system delays. 30 and 35 knot winds produce a small increase on average delays for both piston and jet aircraft and higher maximum delays.

Figure 11. Delay vs. Wind Speed, Wind out of the South, 10 Landings/Hour Average

Wind direction (Figure 12) has a small impact on average system performance. However, the data shows that a 20 knot cross wind caused a jet aircraft to have a delay of 38 minutes and 4 seconds and a piston aircraft to have a delay of 33 minutes and 6 seconds (wind out of the East, 20 knots). Wind out of the west, also a cross wind, resulted in a piston aircraft having a delay of 27 minutes and 23 seconds.

Figure 12. Delay vs. Wind Direction, 20 knot wind, 10 Landings/Hour Average

It can be argued that wind has a bigger impact on piston (slower) aircraft and the observed maximum delay on the jet aircraft is a result of the jet aircraft queuing behind the slower aircraft.

5. Summary

A concept for automated access services to non-tower, non-radar airports during IMC was presented. To investigate the feasibility of the concept, a batch simulation has been developed.

Simulation shows that time separation with implicit sequencing is an effective way to provide automated traffic management in the terminal area. Mixed operations, where fast aircraft and slow aircraft are sharing approach paths, produced higher average and maximum delays than operations with a single type of aircraft.

Access requests based on distance to airport penalizes fast aircrafts. A method based on time to airport will probably result in a more equitable system.

In mixed operations, 10 aircraft per hour average landing rate appears to be the upper acceptable limit. For fast aircraft using the facility, arrival rates of up to 18 aircraft per hour average landing rate produces acceptable results. This is close to the theoretical maximum of 20 aircraft per hour average landing rate.

Preliminary simulations with landing and take off operations show improvement in delays when total operation rates are compared to landing rates. However, this depends on methods used to separate arriving from departing flights. For example, if departing flights can be vertically separated from arriving flights on regions 1 and 6, then reduced delays can be achieved for constant operation rates. Dedicated departure corridors also produce reduced overall delays and higher throughputs. These considerations are dependent on geography and airspace design.

In conjunction to the simulation work, a verification using formal mathematical techniques [12] is being conducted to show that the concept is safe. This is accomplished by mathematically showing that time separation at fixes and the method to grant or deny entry into the SCA guarantees geometrical separation in the airspace.

The concept presented in this paper was developed to show feasibility and to explore methods for verification. It is not the concept of operation being developed for the SATS HVO [1] program. The concept presented in this paper is expected to evolve and change as constraints are better defined and more results from simulation and experiments are obtained.

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